What the Standard Model May Not Want Us To Know

Searching For a Nonperturbative Regulator for Chiral Gauge Theories

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work done with David B. Kaplan
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Motivation: Self-Consistent Chiral Gauge Theories

Big Question 1: What are the basic ingredients of self-consistent chiral gauge theories (χGT)?

- Electroweak experiments probe weakly coupled χGT
- Perturbative regulator provides controlled theoretical description of perturbative phenomena
- Do not currently have experimental access to nonperturbative behavior

To address this question, must find a nonperturbative regulator

Motivation: Nonperturbative Regulator for χGT

Big Question 2: Do the properties of (nonperturbative) regulators indicate new physics?

- No regulator preserves $U(1)_A$: No 9^{th} Goldstone Boson and $U(1)_A$ is not a symmetry of QCD

- U(1) Landau Pole: Need new physics in the UV

    - Standard Model gauge groups might unify

- Nonperturbative regulator for χGT could reveal new particles hiding in the Standard Model

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Finding nonperturbative regulator could be more than just an academic exercise

Motivation: Nonperturbative Regulator for χGT

Vector Theory (QED, QCD)

- **Real** fermion representation
- Gauge symmetries **allow** fermion mass term
- Gauge invariant massive regulator (Pauli-Villars) **can** be used
- **Known** lattice regulator

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Chiral Theory (Electroweak)

- **Complex** fermion representation
- Gauge symmetries **forbid** fermion mass term
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- **No widely accepted** lattice regulator (Eichten and Preskill '86, Narayanan and Neuberger '94, Lüscher '99, etc)

** Exception: Infinite number of Pauli Villars*

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Is this a technical issue or indicative of new physics?

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Technical Question: Define Measure for χGT

Observables are calculated by integrating over gauge fields with some measure

$$\langle F(A)\rangle = \frac{\int [DA] e^{-S(A)} \Delta(A) F(A)}{\int [DA] e^{-S(A)} \Delta(A)}$$

- F(A) is the observable
- S(A) is gauge action (Maxwell or Yang Mills)
- Δ(A) is due to fermions

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- Δ(A) is due to fermions
  - Δ(A) for Dirac fermion is well-known

$$\Delta_{DF}(A) = \det \not{D}(A)$$

  - But it is not well know how to define Δ(A) for chiral fermion

$$\Delta_{\chi F}\Delta^*_{\chi F} = \Delta_{DF}$$

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What is the fermionic contribution to the measure for χGT?

- Need definition so that effective action is local and analytic

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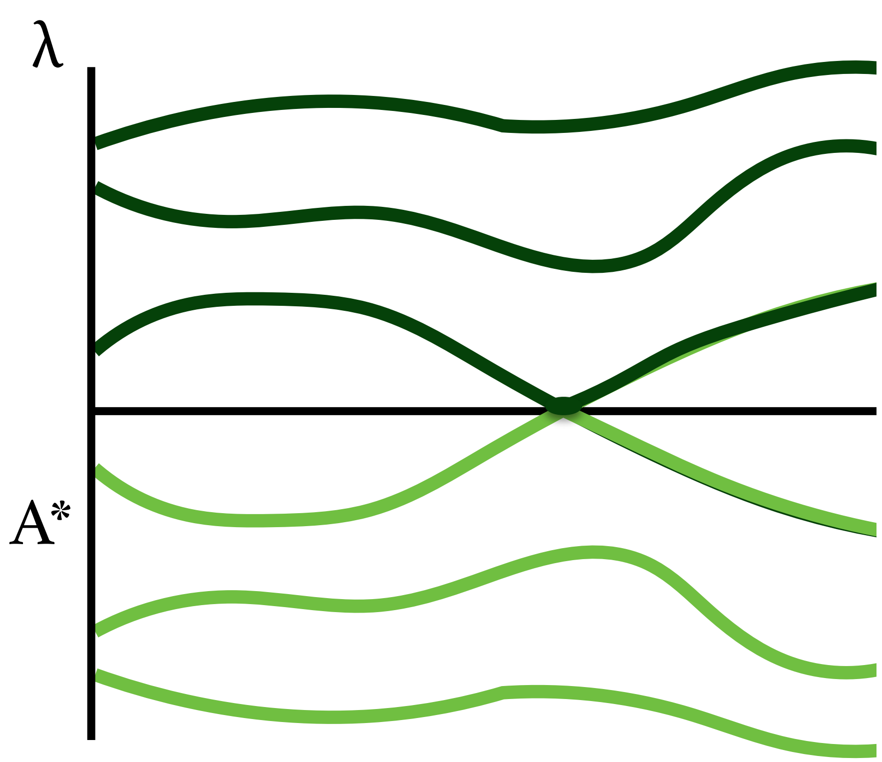
Dirac operator eigenvalues



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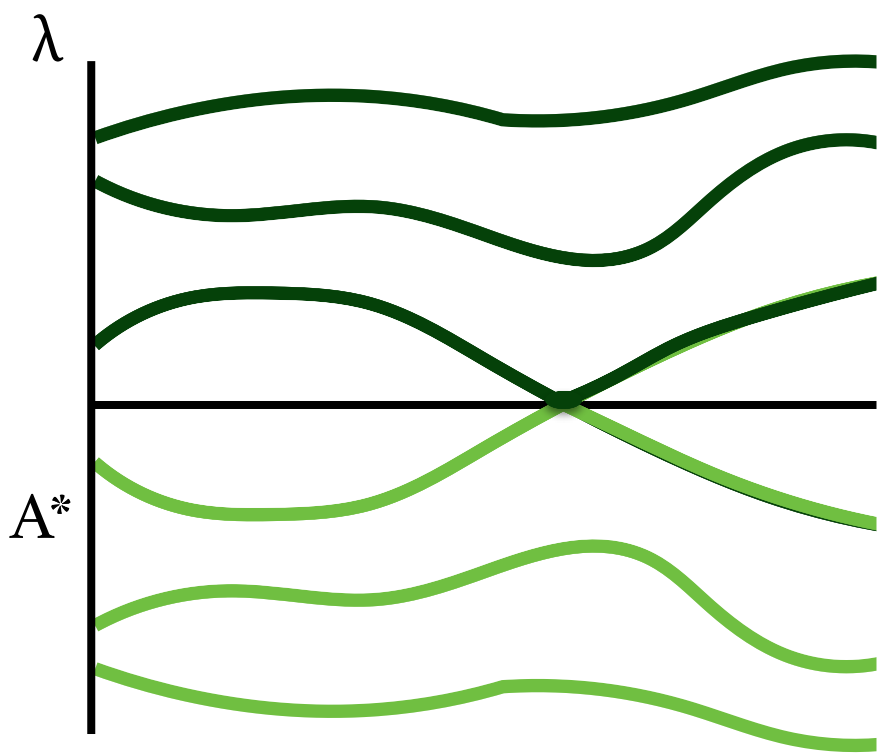

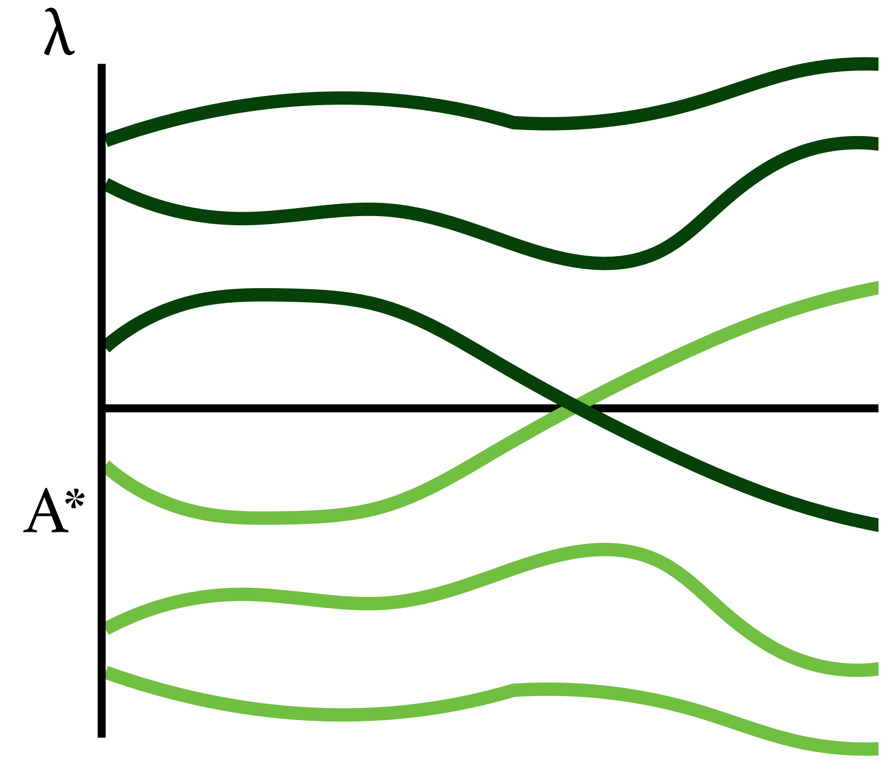

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Motivation: Lattice Regulate Chiral Gauge Theory

Continuum Field Theory

- Theories with chiral symmetries can have anomalies

- Standard Model contains global anomalies

- Chiral gauge theories only well-behaved if no gauge anomalies

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Lattice Field Theory

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- Lattice must explicitly break global chiral symmetry to reproduce anomaly
- Lattice must somehow distinguish anomalous and anomaly-free gauge theories

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How does one construct a lattice theory that has the correct continuum behavior?

Criteria for Successful Nonperturbative Regulator

Criteria 1: Road to failure for anomalous fermion representations

Criteria 2: Reproduces all other perturbative results

- Only have experimental verification of weakly coupled chiral gauge theory
- Other regulators are all perturbative
- Might discover unexpected nonperturbative phenomena

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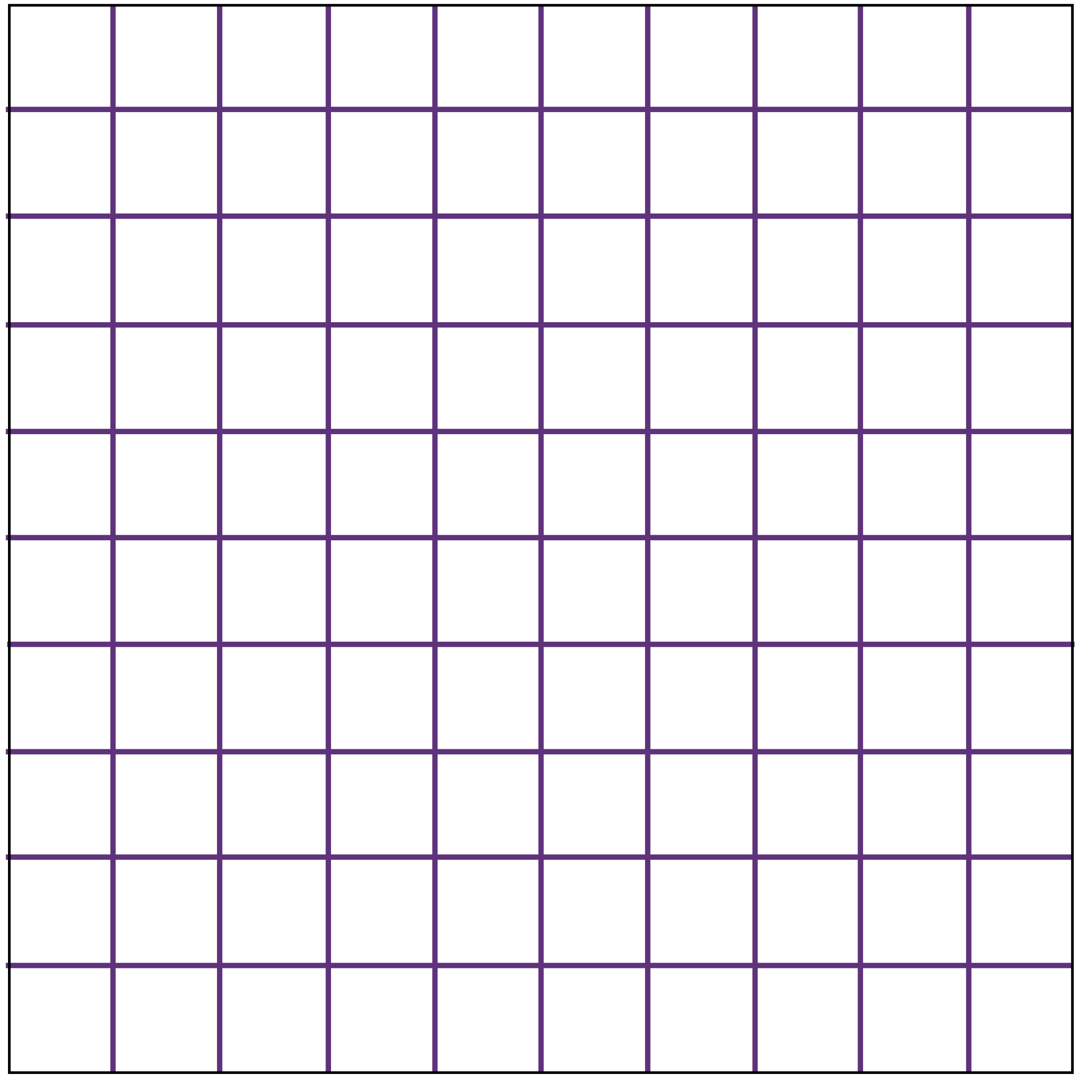
*this is what the Standard Model might be hiding

Chiral Symmetry on the Lattice

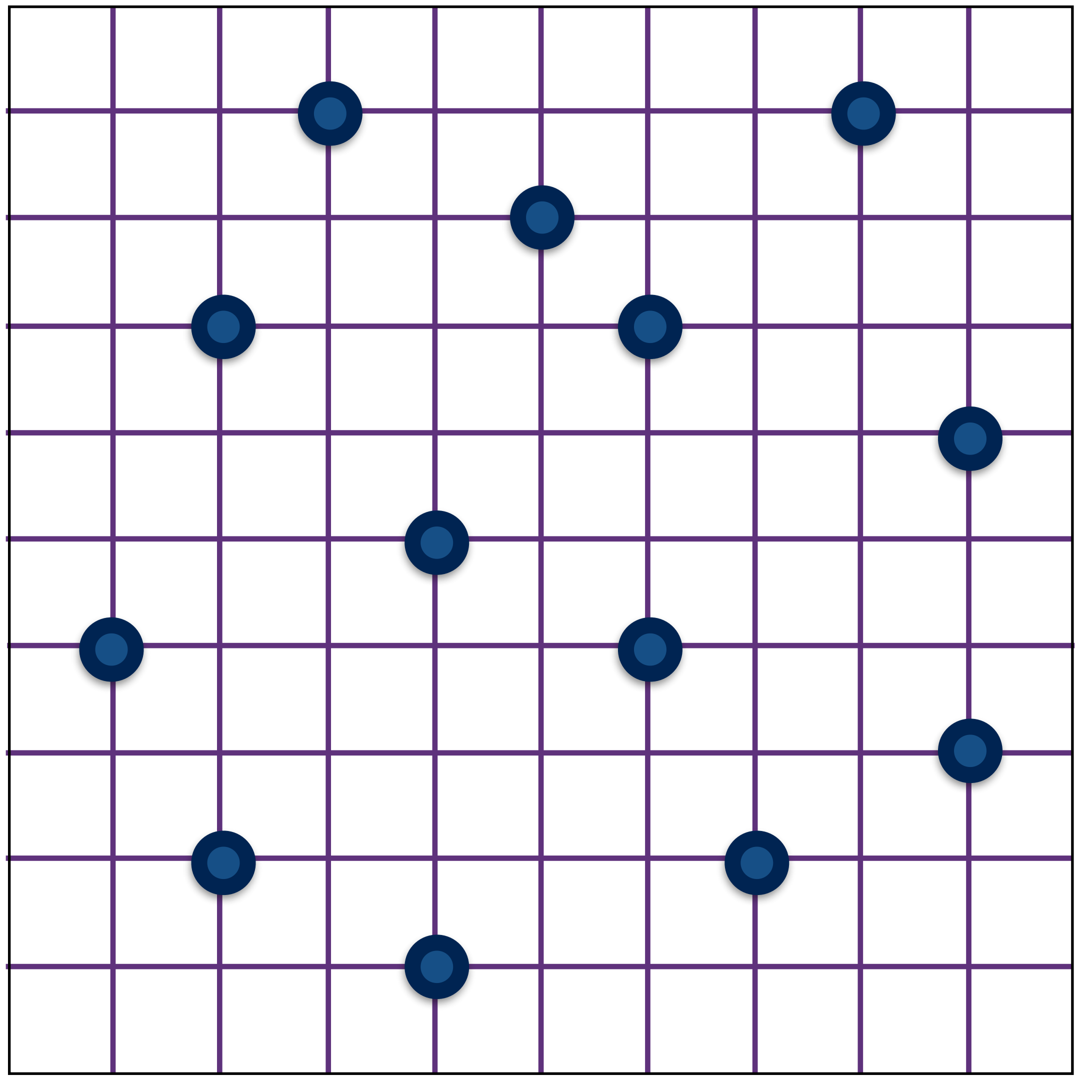
1. Discretize spacetime i.e. start with a lattice



Chiral Symmetry on the Lattice

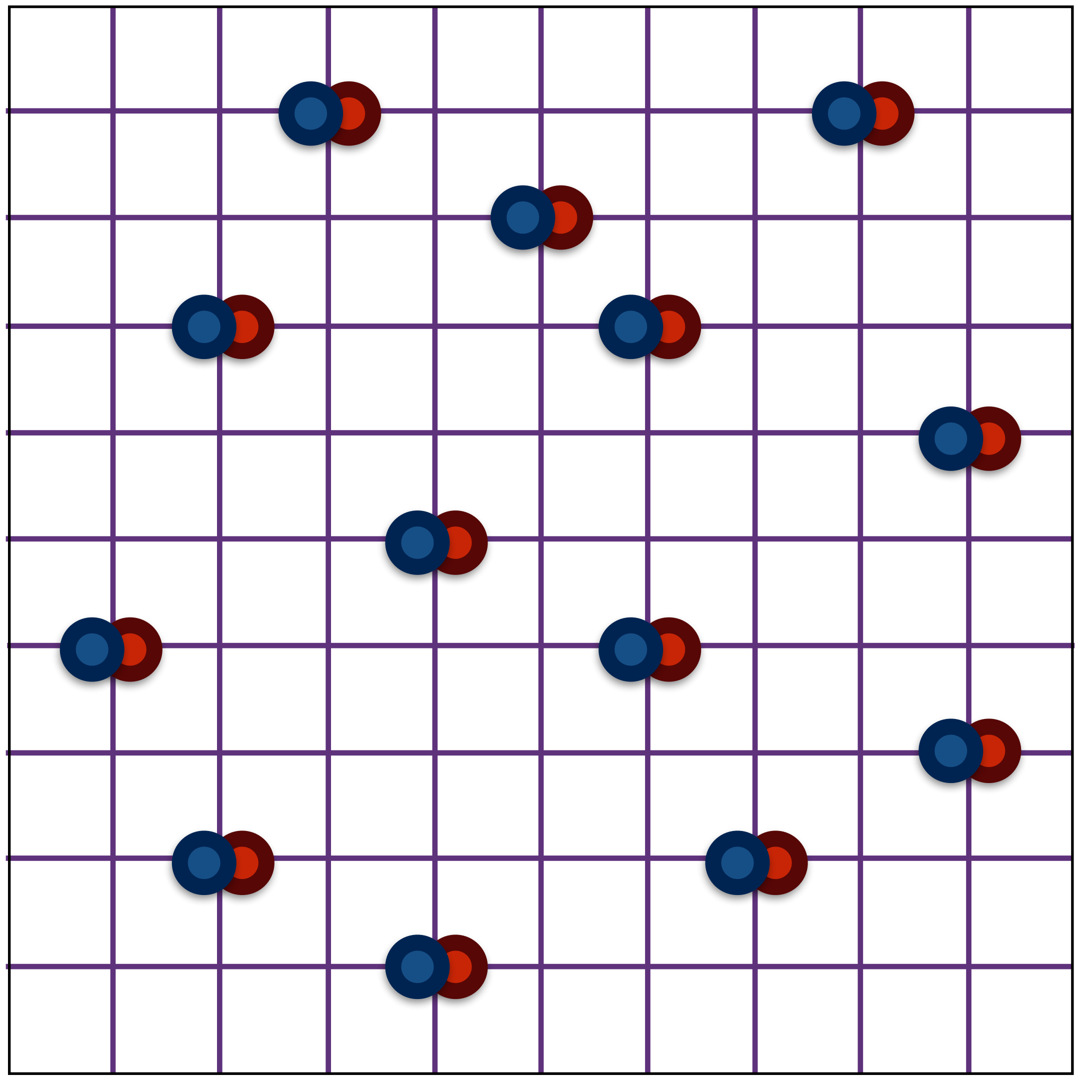
1. Discretize spacetime i.e. start with a lattice

2. Put down left handed Weyl fermions



Chiral Symmetry on the Lattice

1. Discretize spacetime i.e. start with a lattice
2. Put down left handed Weyl fermions
3. Lattice automatically adds equal number of right handed Weyl fermions



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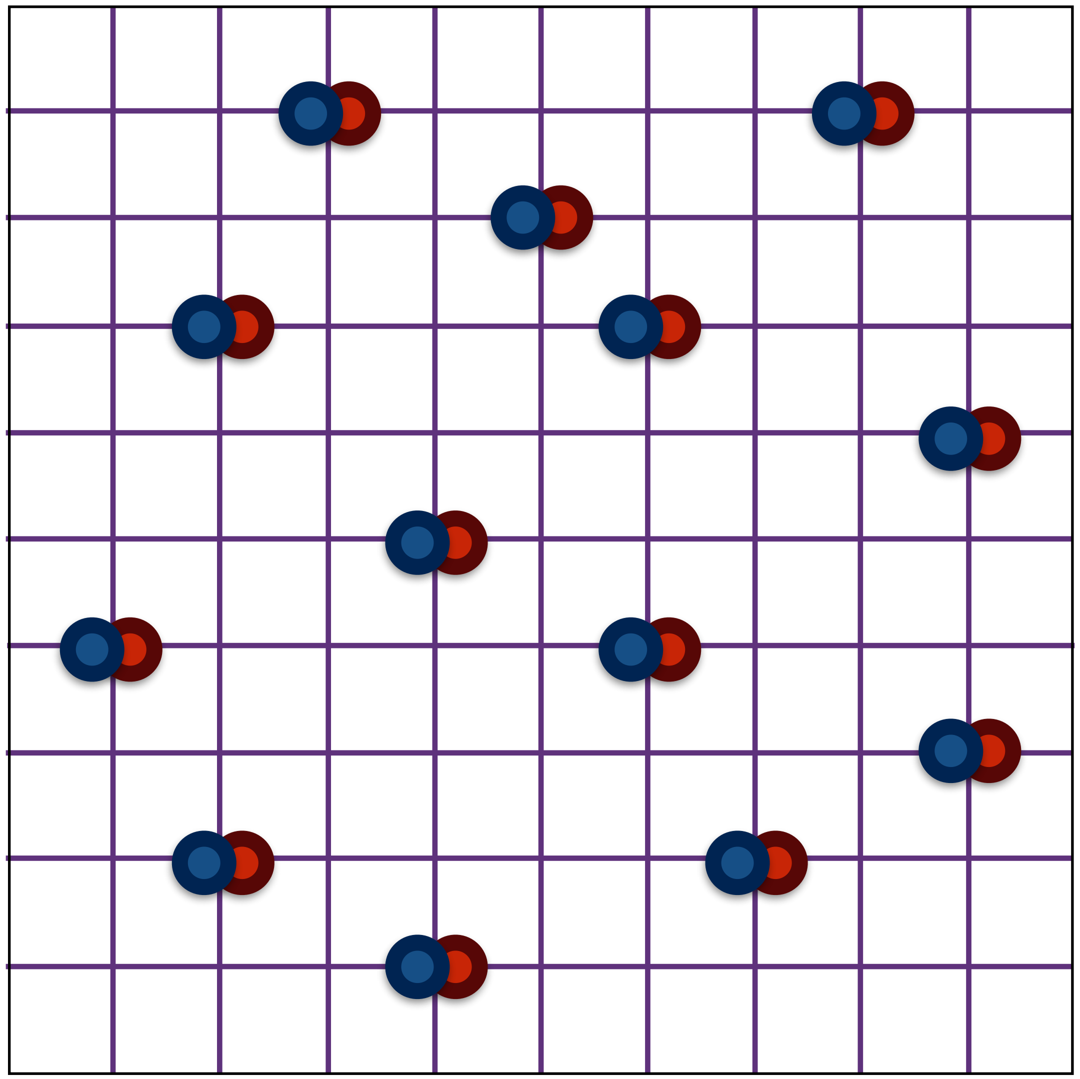


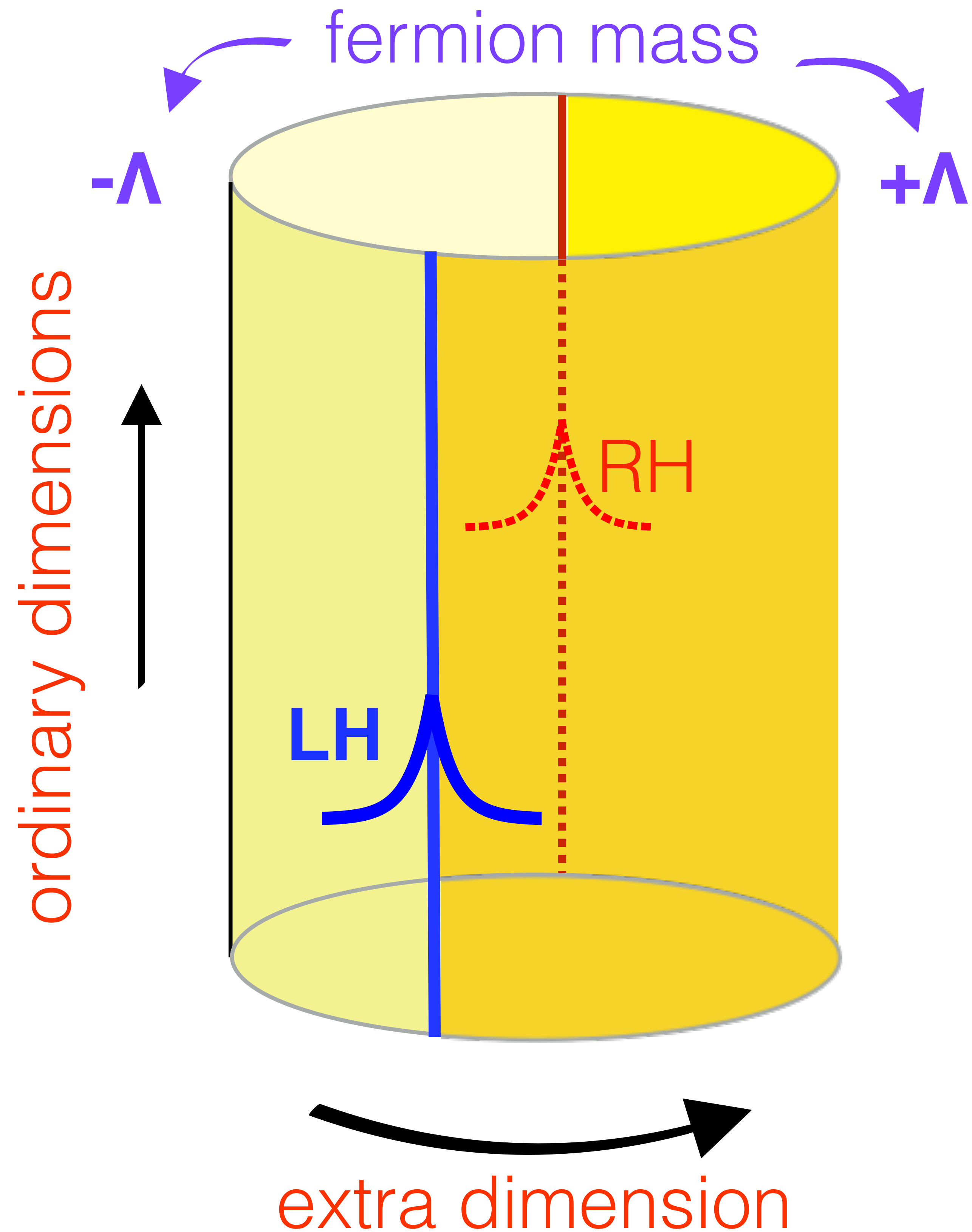
Need mechanism to distinguish left handed and right handed fermions

Global Chiral Symmetries

Domain Wall Fermions (DWF)

(Kaplan, '92)

- Introduce extra (compact) dimension, s
- Fermion mass depends on s
- Massless modes localized on mass defects
- Gauge fields independent of s
- Anomaly due to bulk fermions carrying charge between mass defects
- Condensed matter physicists would call this a topological insulator



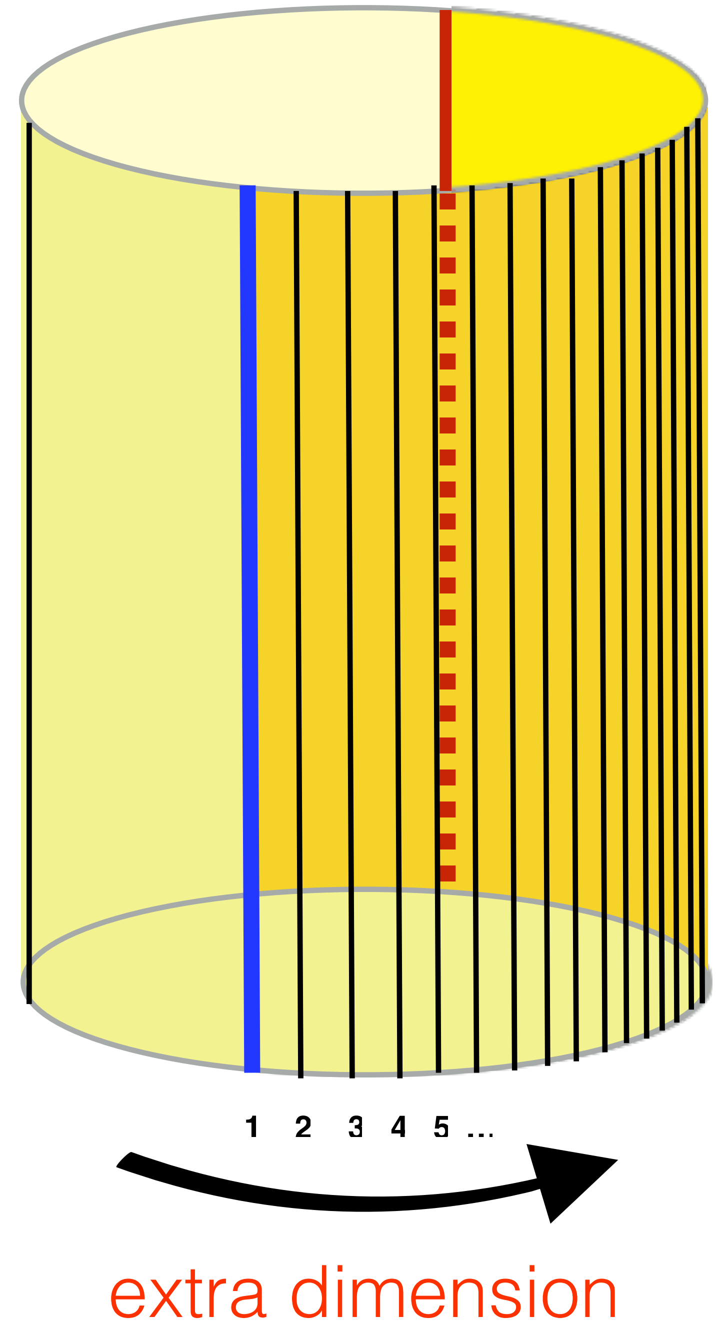
Global Chiral Symmetries

DWF always give rise to a vector gauge theory

- DWF 5d action is equivalent to action for an infinite number of 4d fermions
- Discretized extra dimension can be interpreted as flavor quantum number

$$\overline{\psi}\gamma_5\partial_s\psi \to \overline{\psi}_n\gamma_5\left(\psi_{n+1} - \psi_n\right)$$

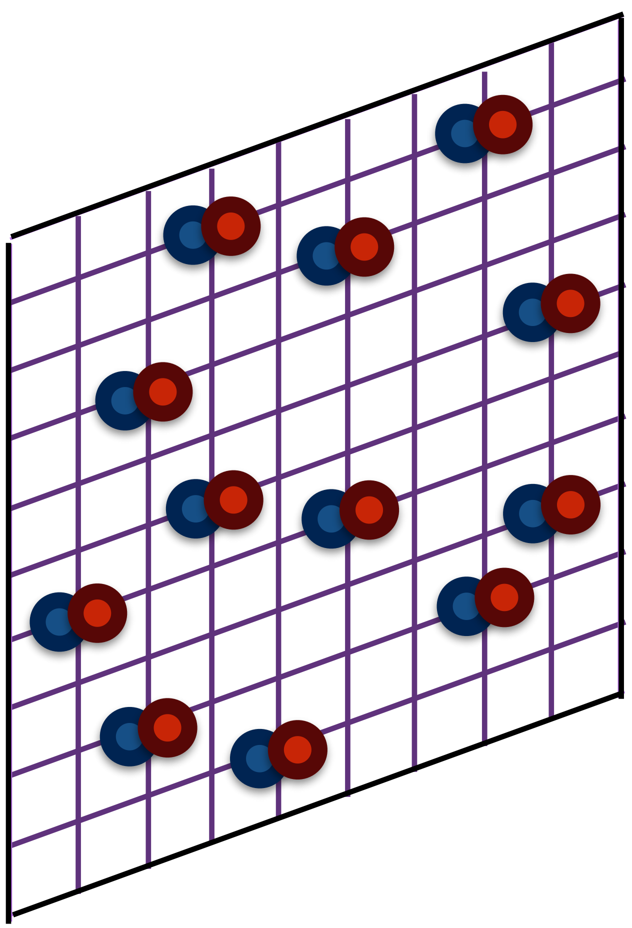
Every flavor must be in same gauge group representation



Decoupling Mirror Fermions

Mirror fermions must have different interactions in order to decouple

1. Add extra dimension - Domain Wall Fermions



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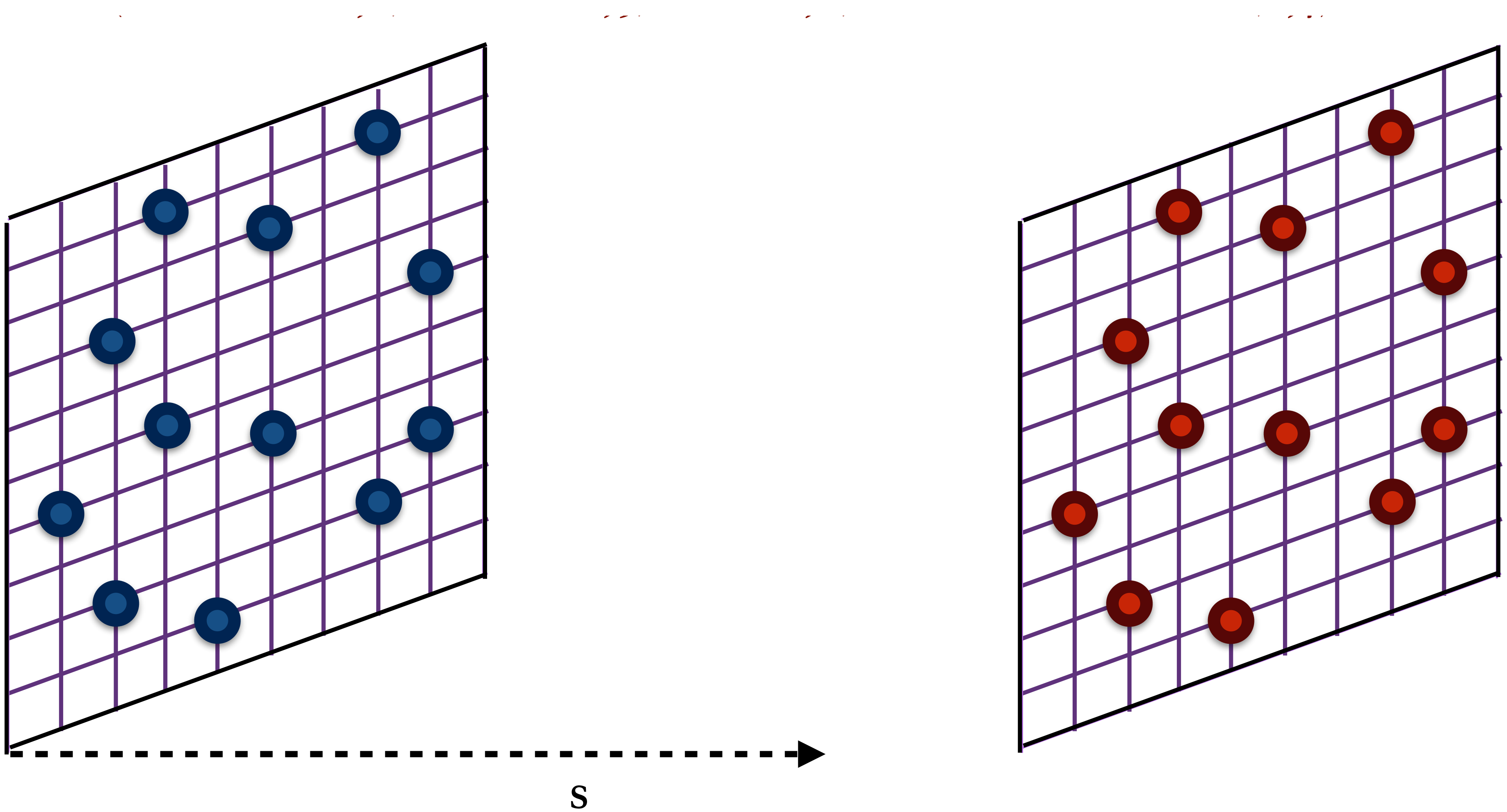
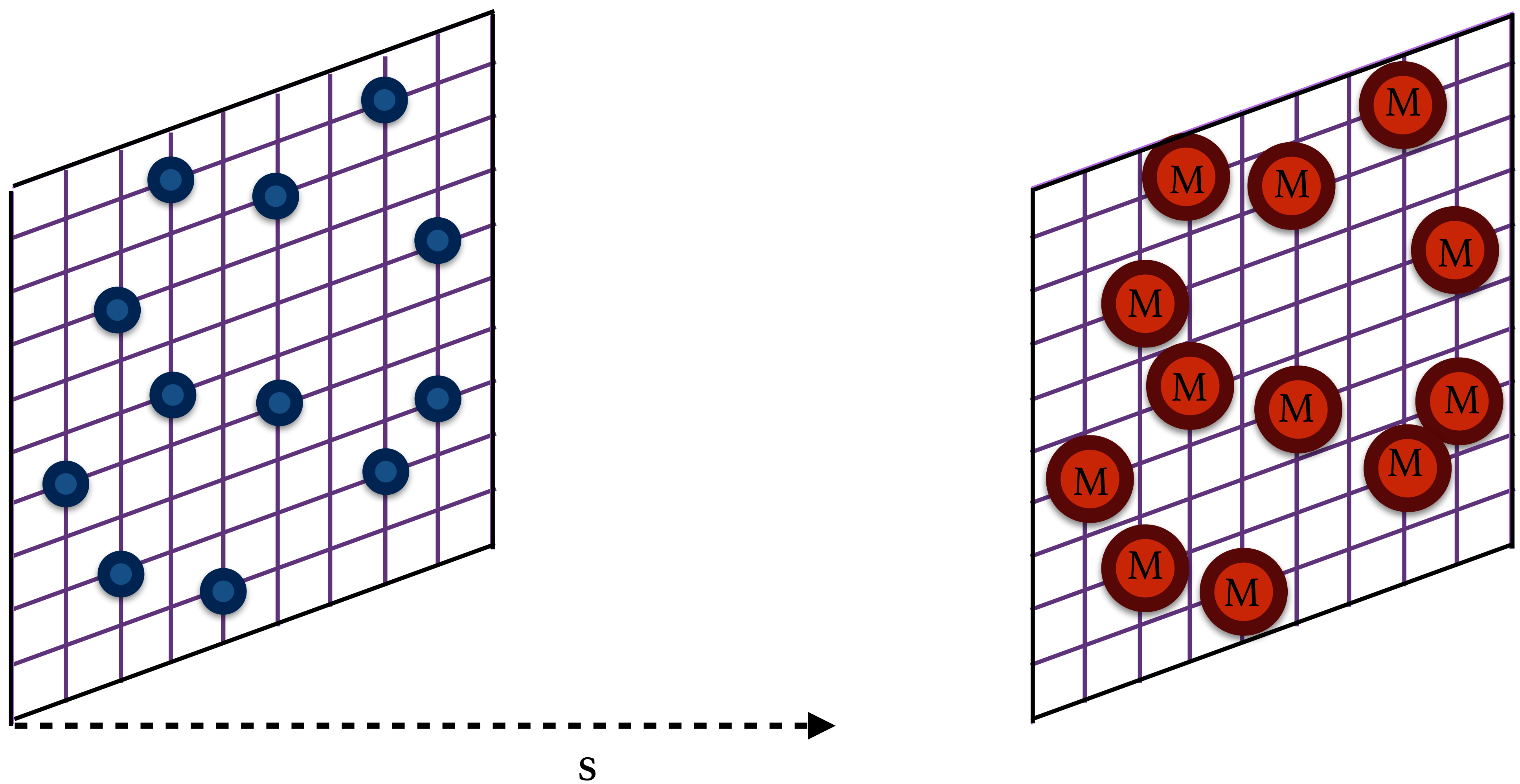


Decoupling Mirror Fermions

Mirror fermions must have different interactions in order to decouple

1. Add extra dimension - Domain Wall Fermions

2. Give mass to the mirror fermions, breaking gauge invariance on the lattice (Borrelli et al '92, Rossi et al '93, Shamir '98, Golterman and Shamir, '97)

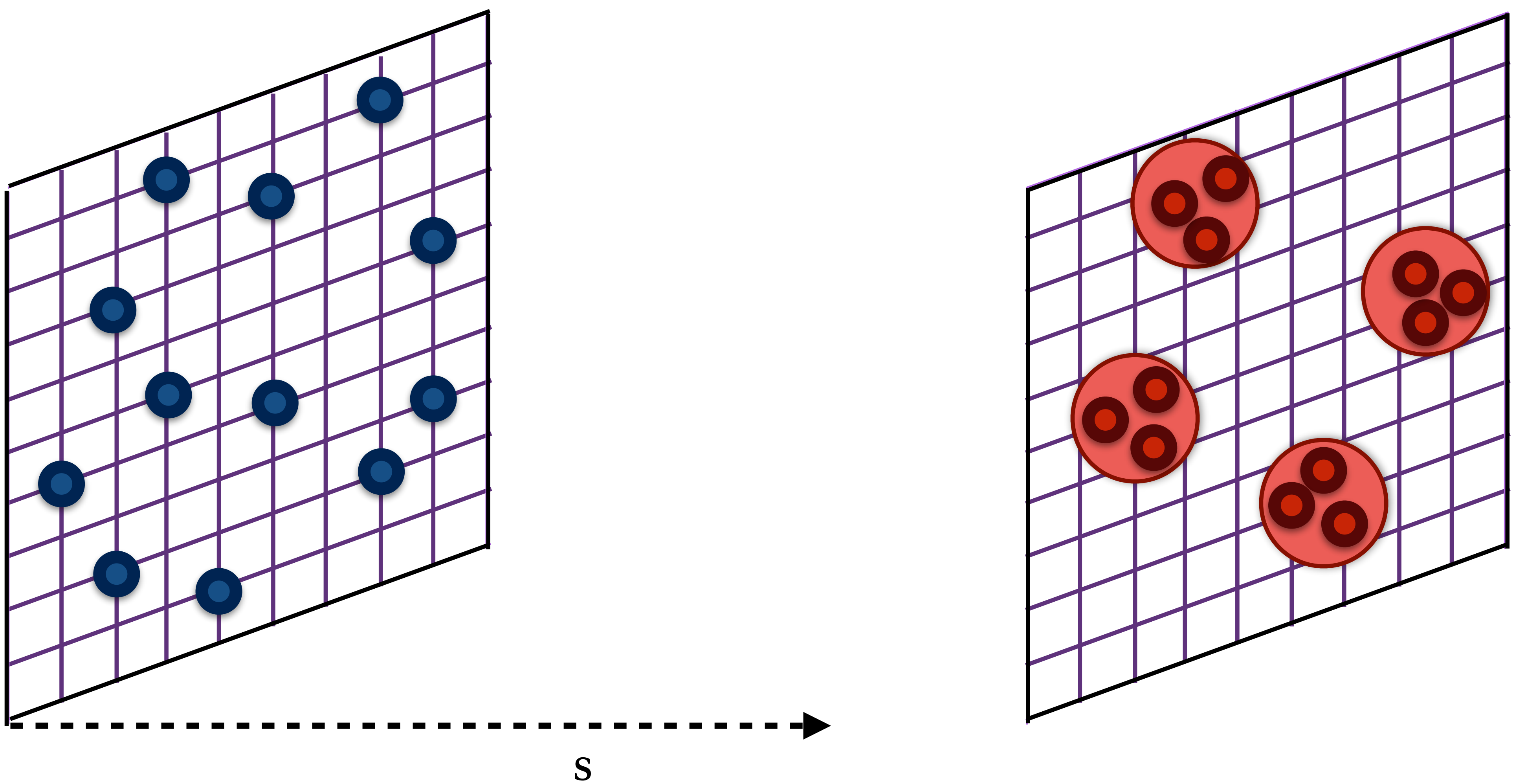


Decoupling Mirror Fermions

Mirror fermions must have different interactions in order to decouple

1. Add extra dimension - Domain Wall Fermions

2. Confine only mirror fermions, using appropriately chosen and tuned interactions (Eichten and Preskill '86, Golterman, Jansen and Vink '93)



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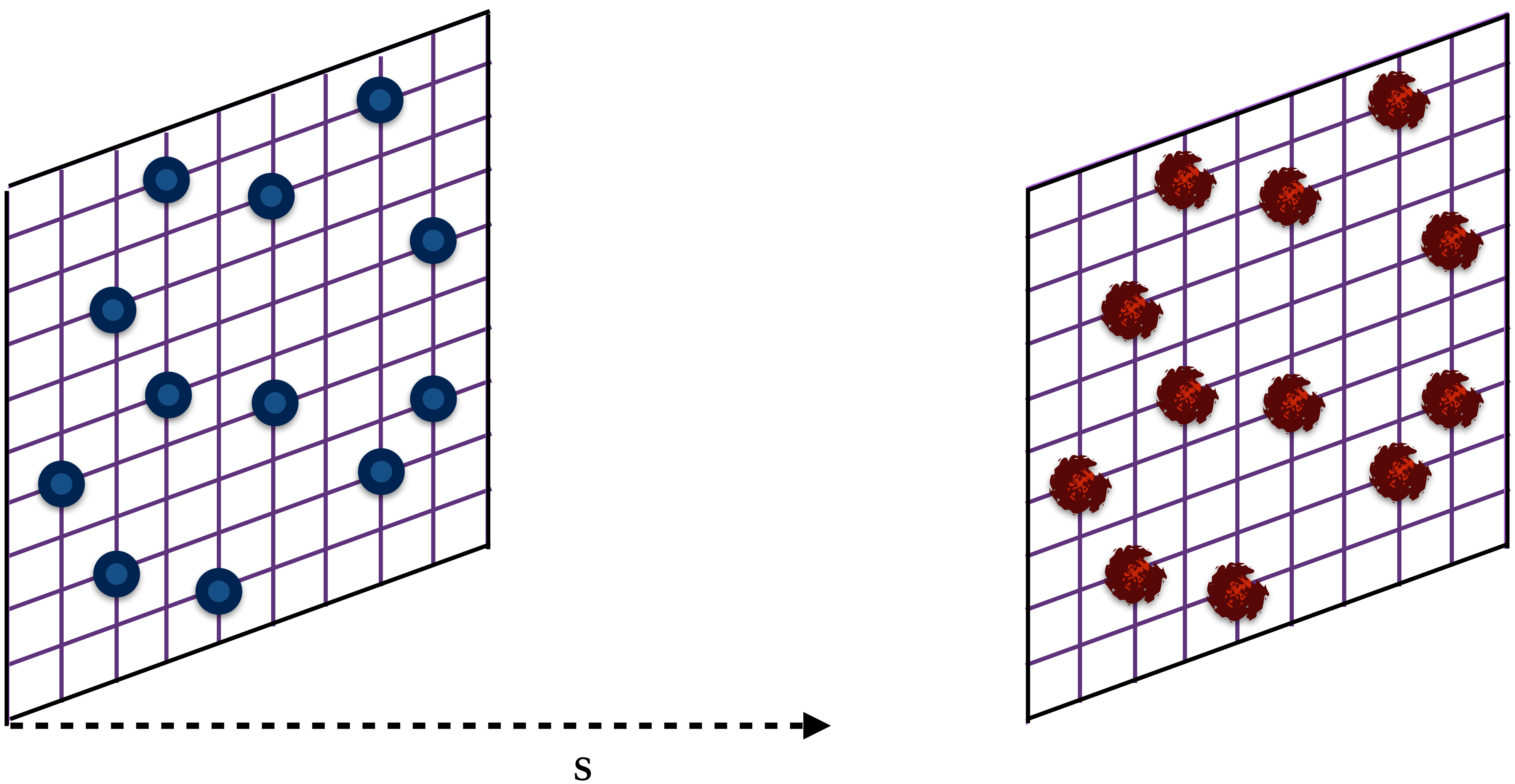
Mirror fermions must have different interactions in order to decouple

1. Add extra dimension - Domain Wall Fermions

2. Give mirror fermions soft form factors (DMG and Kaplan '15)



Gauged Chiral Symmetries

Idea: Localize gauge fields around one defect via gradient flow
(DMG and Kaplan, '15)

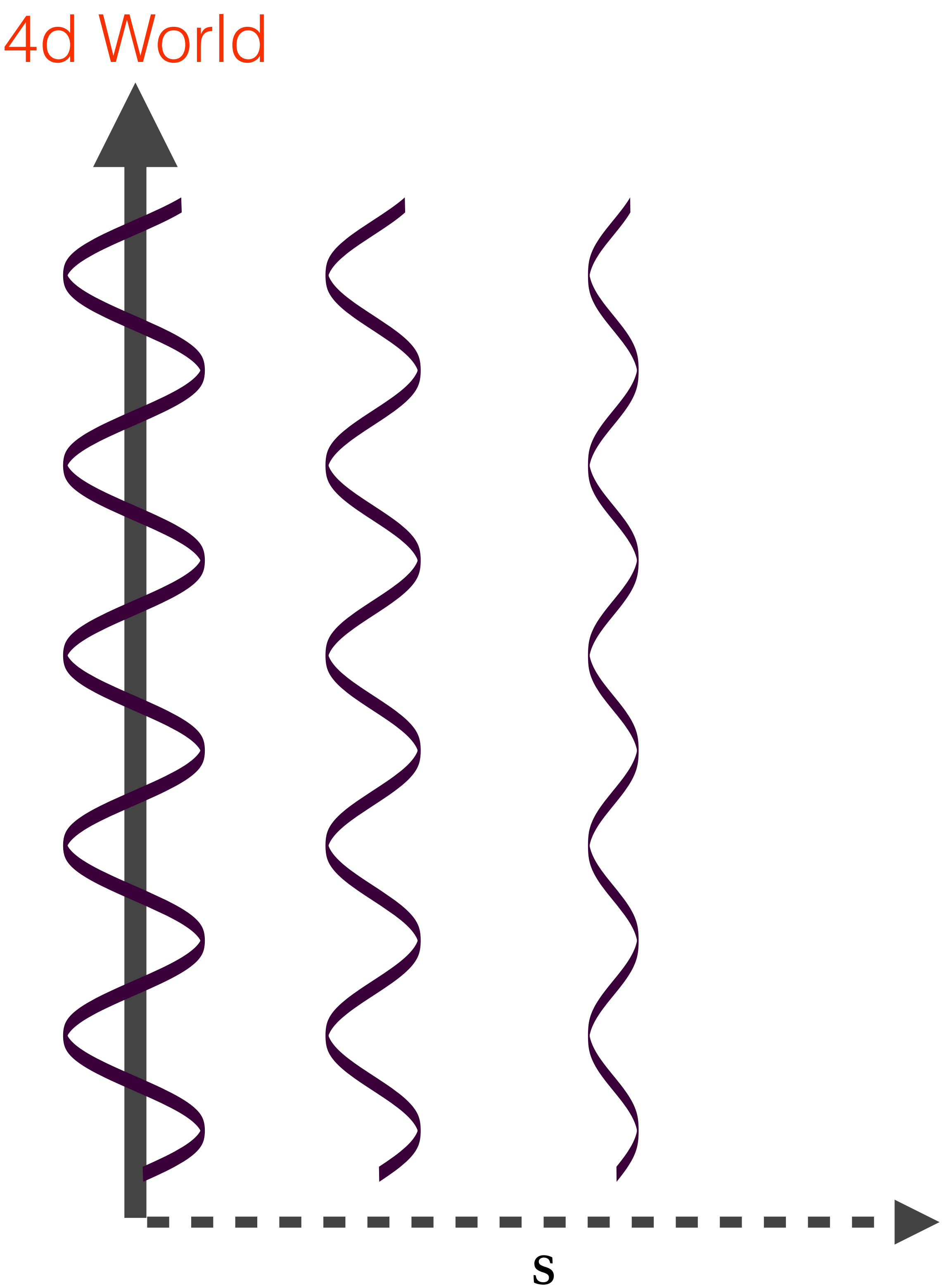
Gradient Flow (Lüscher, '11)

- Utilizes extra dimension
- Start with any gauge field, A_μ
- Extend gauge field into the bulk via particular flow equation

Flow Eq: $\partial_s \bar{A}_\mu = D_\nu \bar{F}_{\nu\mu}$ BC: $\bar{A}_\mu(x,0) = A_\mu(x)$

  - Behaves like heat equation
  - **Damps out high momentum modes**

Flow Equation: 2d/3d QED Example



Write A_μ in terms of gauge and physical degree of freedom

$$\bar{A}_\mu = \partial_\mu \bar{\omega} + \epsilon_{\mu\nu}\partial_\nu \bar{\lambda}$$

Flow Eqs.

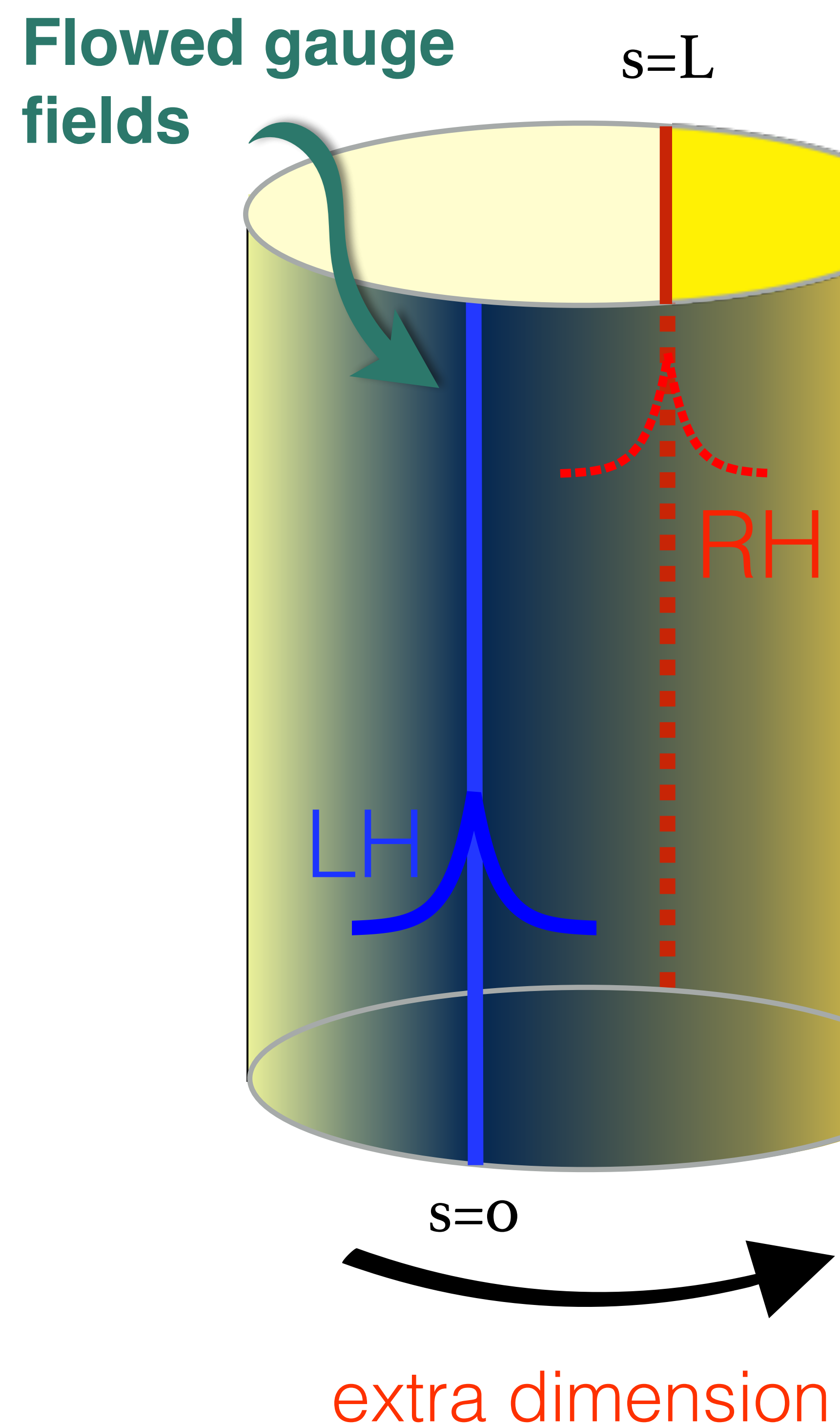
$$\partial_s \bar{\lambda} = \Box \bar{\lambda} \qquad \partial_s \bar{\omega} = 0$$

Flow in extra dimension damps out high momenta modes

Combine Domain Wall Fermions and Gradient Flow

Idea: Localize gauge fields at one defect via gradient flow

- Gauge field at s= 0 is quantum gauge field $A_\mu(x)$
- Bulk gauge field $\bar{A}_\mu(x,s)$ obeys flow equation
- Flow is symmetric around s=0
- RH modes have soft form factor coupling to physical degrees of freedom



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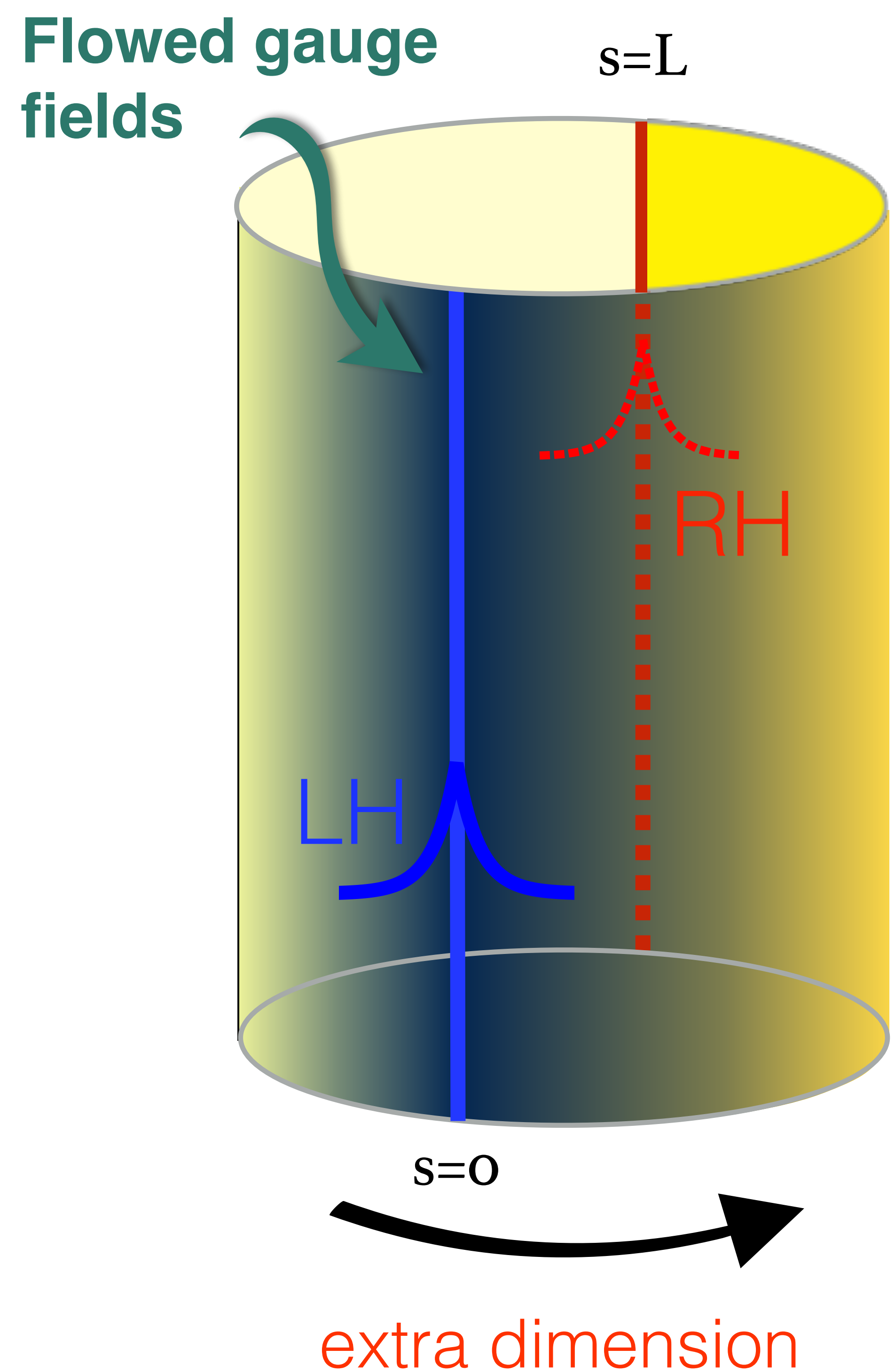
$$e^{-\xi p^2 L/\Lambda}$$



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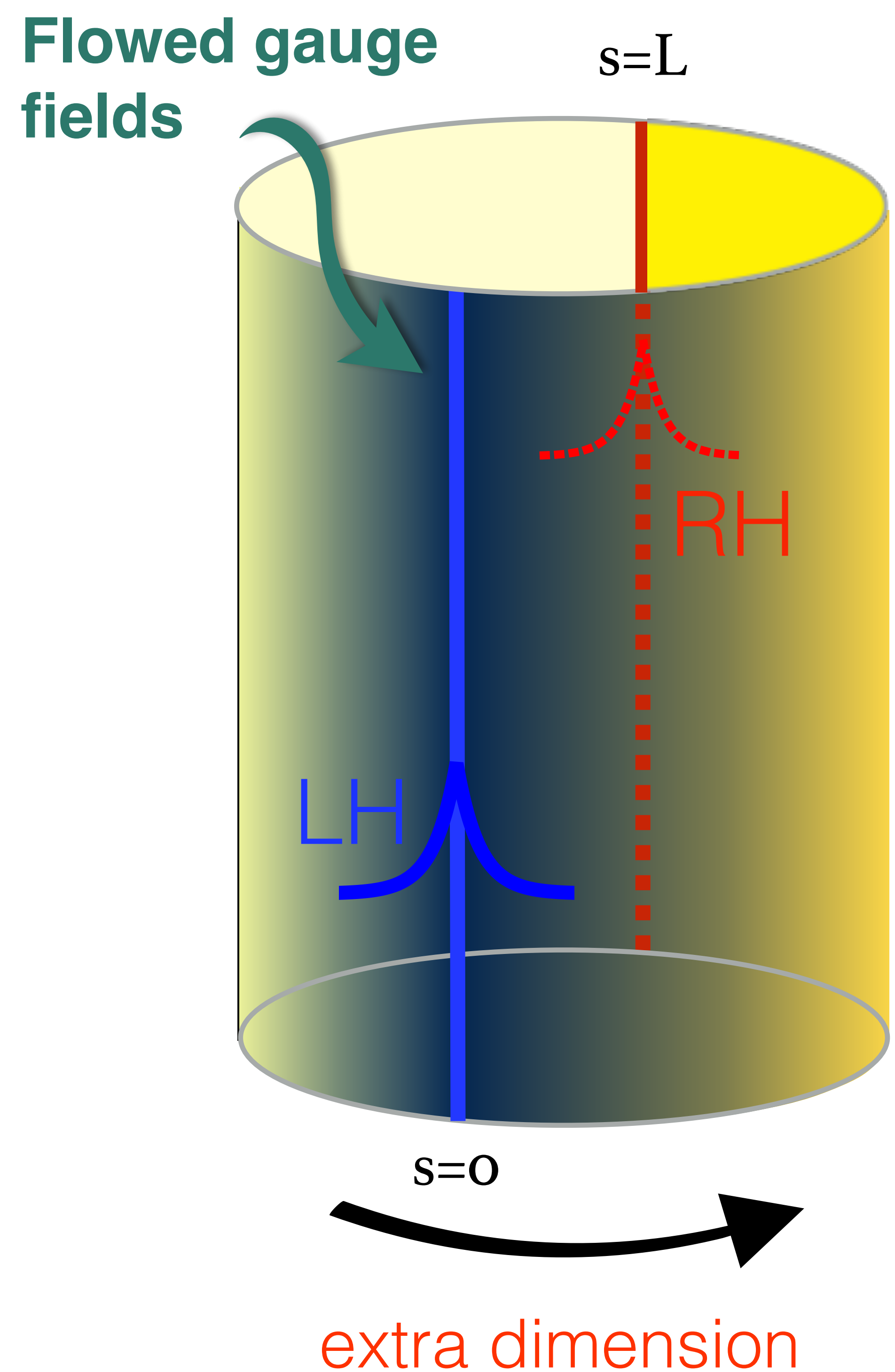
Photon Momentum

Wall separation



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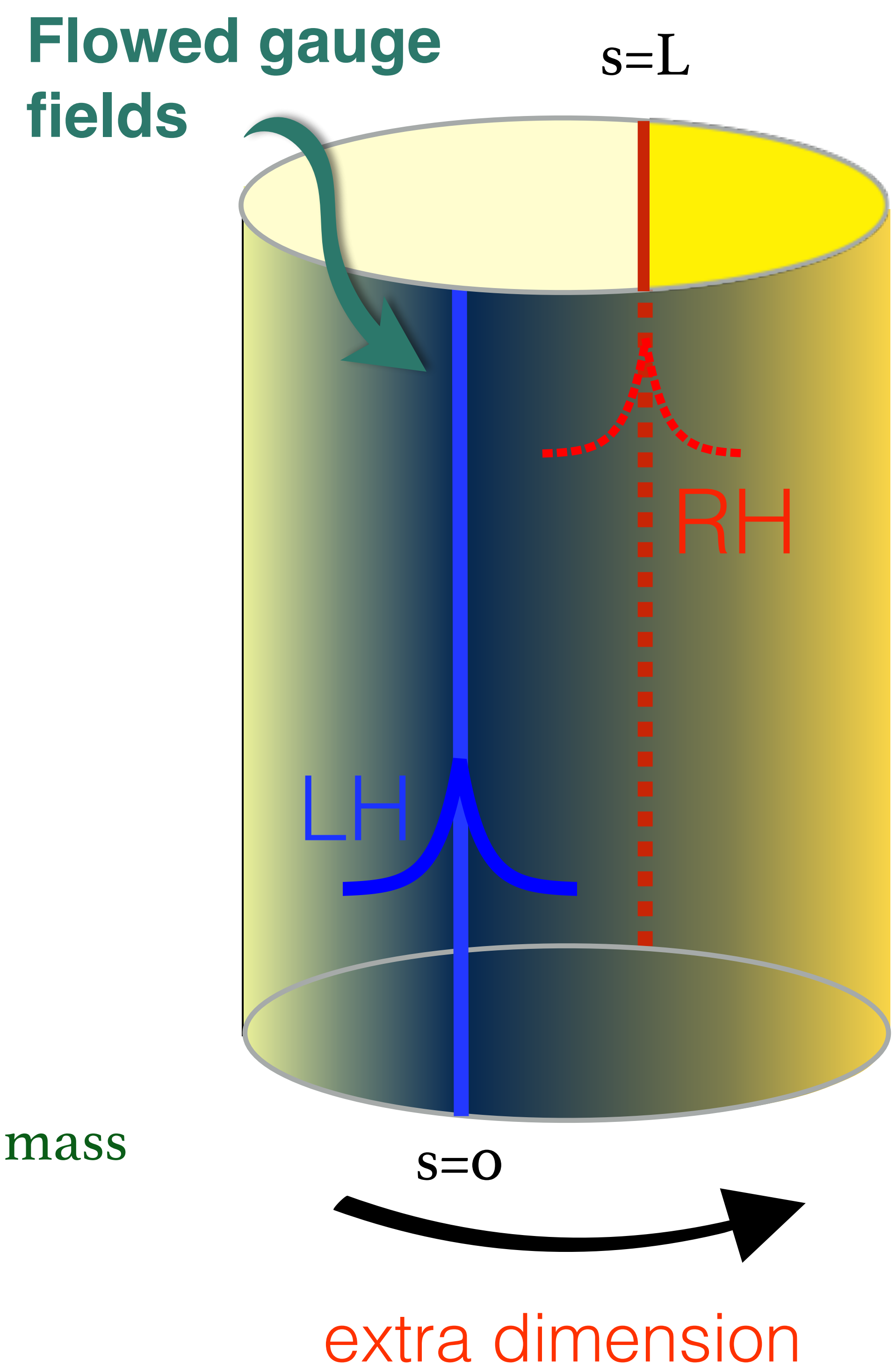
Flow parameter

$$e^{-\xi p^2 L/\Lambda}$$

Bulk fermion mass



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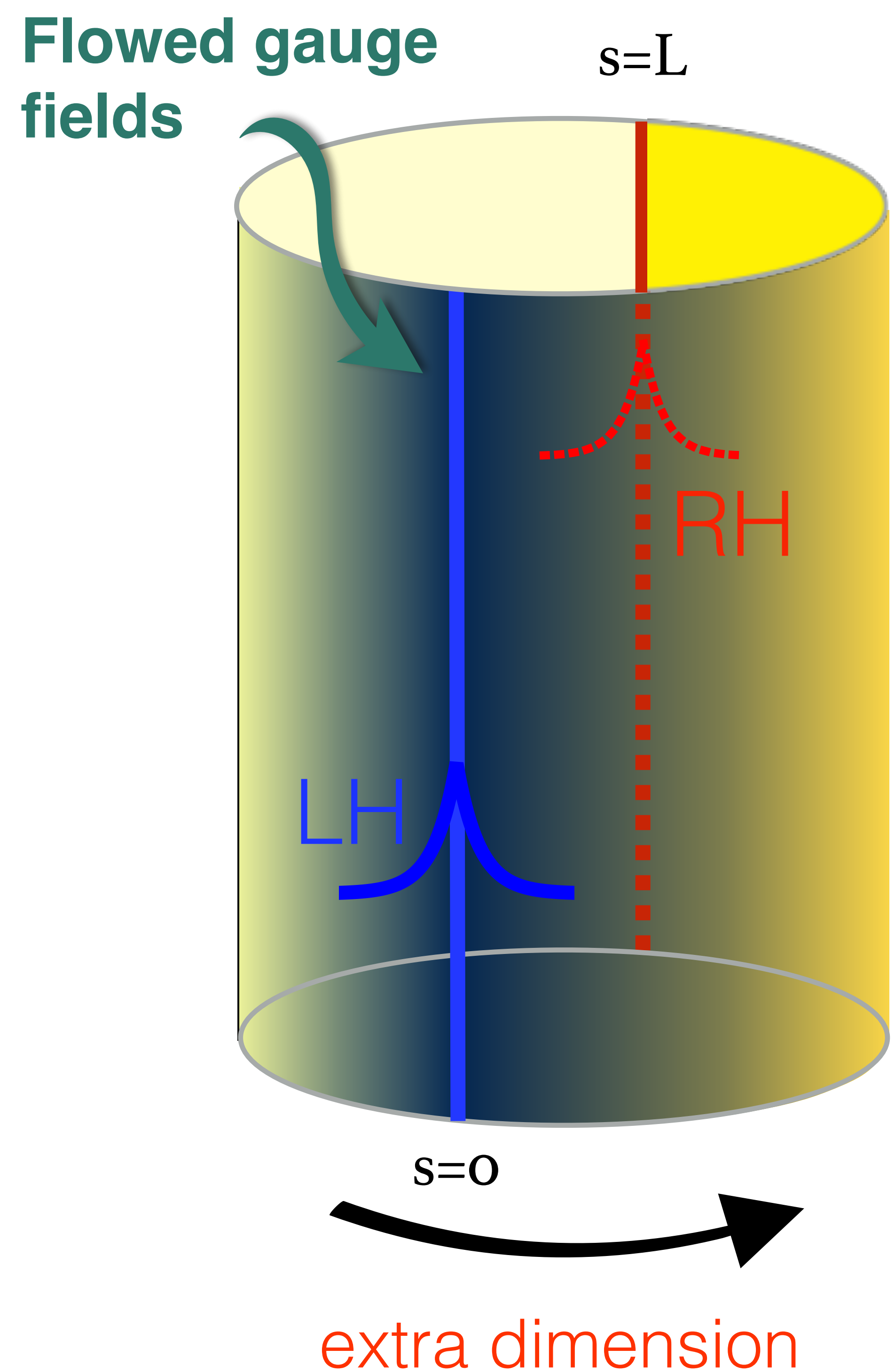
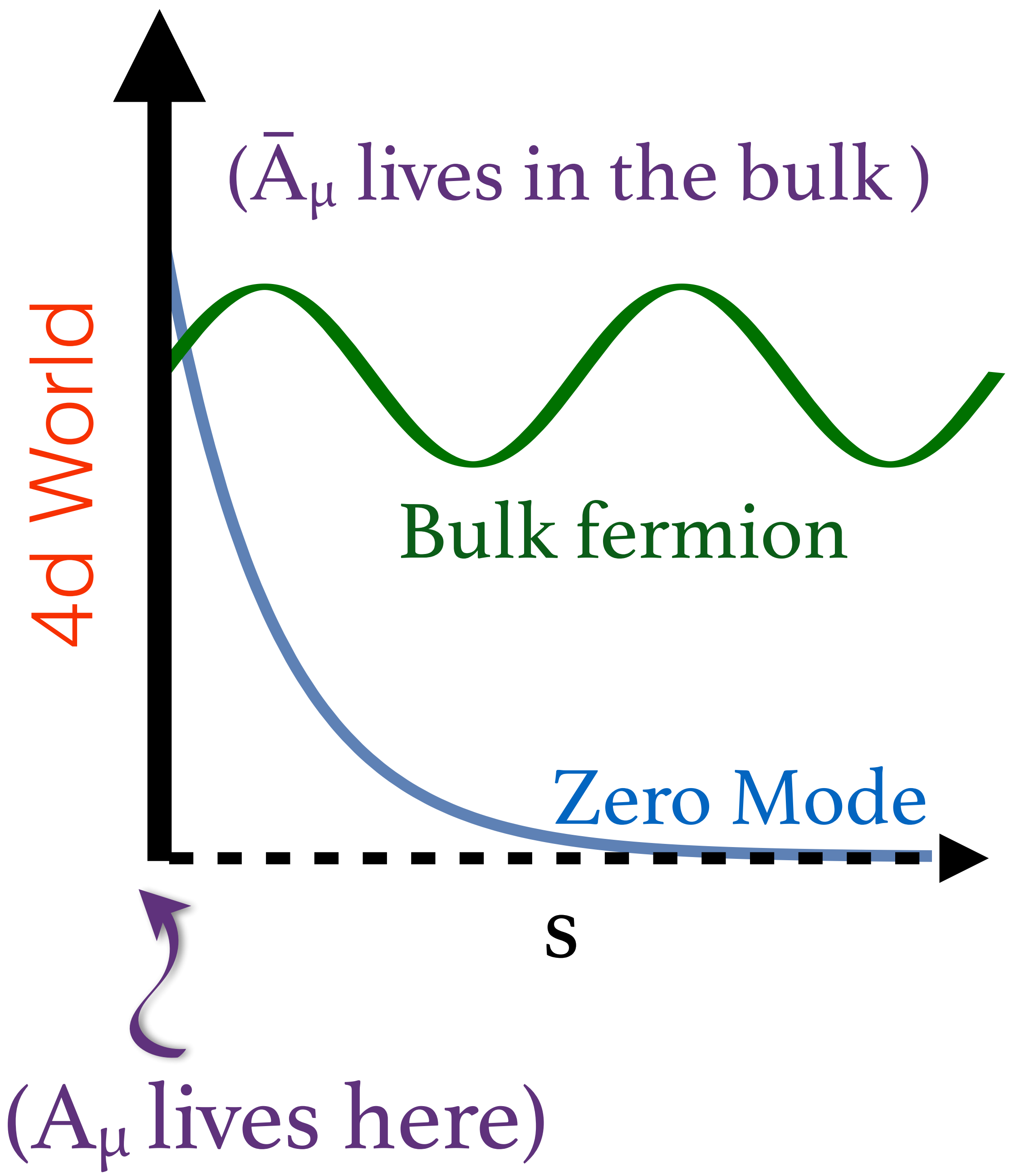
- LH and RH modes couple equally to gauge degrees of freedom



Anomalies and Callan-Harvey Mechanism (Callan and Harvey, '84)

Integrating out bulk fermions generates a Chern-Simons term



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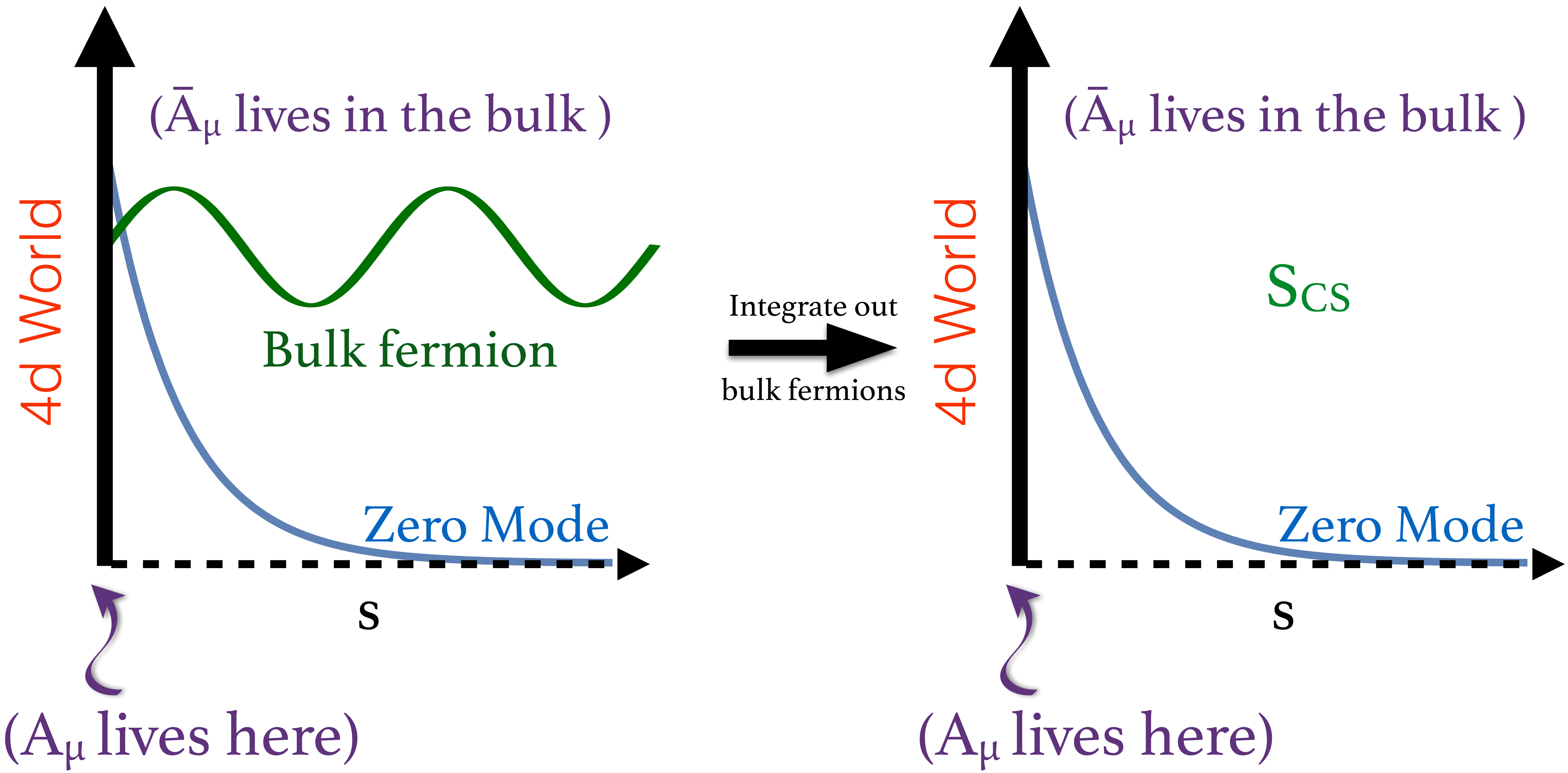

Anomalies and Callan-Harvey Mechanism (Callan and Harvey, '84)

- Integrating out bulk fermions generates a Chern-Simons term
- In 3 dimensions, the Chern Simons action is

$$S_3^{\text{bulk}} = c_3 \frac{\Lambda}{|\Lambda|} \int (\epsilon(s) - 1) \, \text{Tr} \left(\bar{F} \bar{A} - \frac{1}{3} \bar{A}^3 \right)$$

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CS only depends on sign of domain wall mass

Fermion Contribution

Pauli Villars Contribution

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Fermion Contribution

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- This approximation is only valid far away from domain wall

Anomalies and Callan-Harvey Mechanism

- Consider 3 dimensional QED with flowed gauge fields

$$S_3^{\text{bulk}} = 2e^2 c_3 \frac{\Lambda}{|\Lambda|} \int dx^2 dy^2 \left(\frac{\partial_\mu \partial_\alpha}{\Box} A_\alpha(x) \right) \Gamma(x-y) \left(\frac{\partial_\mu \partial_\beta}{\Box} \epsilon_{\beta\gamma} A_\gamma(y) \right)$$

  - No gauge field in 3rd dimension

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Serves as an IR cutoff

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Anomaly Cancellation and Nonlocality

- DWF with flowed gauge fields gives rise to a nonlocal 2d theory

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This is exactly equivalent to the requirement that the chiral fermions be in an anomaly free representation

Proposal for Chiral Gauge Theory Measure

Recall that the goal is to be able to define a chiral fermion measure

$$\langle F(A) \rangle = \frac{\int [DA] e^{-S(A)} \Delta(A) F(A)}{\int [DA] e^{-S(A)} \Delta(A)}$$

Our proposal:

$$\Delta(A) = \prod_i \frac{\det\left[\not{D}(\bar{A}) - \Lambda_i \epsilon(s)\right]}{\det\left[\not{D}(\bar{A}) - \Lambda_i\right]} \qquad \partial_s \bar{A}_\mu = \frac{\xi \epsilon(s)}{|\Lambda|} D_\nu \bar{F}_{\nu\mu}$$

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One factor for each species of fermion

5d Dirac operator with flowed gauge field

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- Mirror fermions decouple for infinitely large wall separation
- Target d-dimensional theory is local if fermions are in an anomaly free representation
- Effective action is what one would expect for chiral fermion (did not show here)

Open Questions

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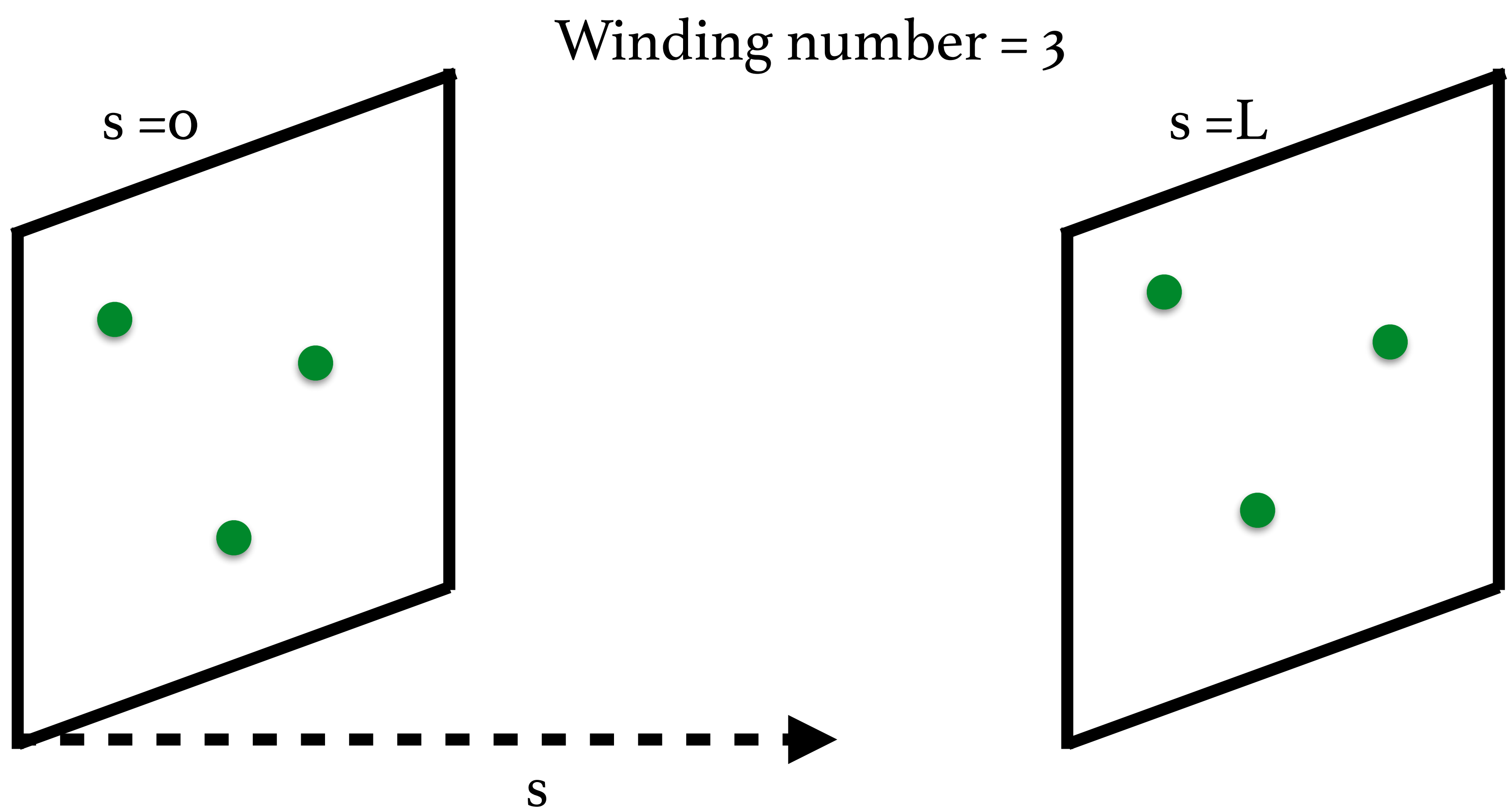
Current work in progress

Topological Gauge Configurations - Weak Coupling



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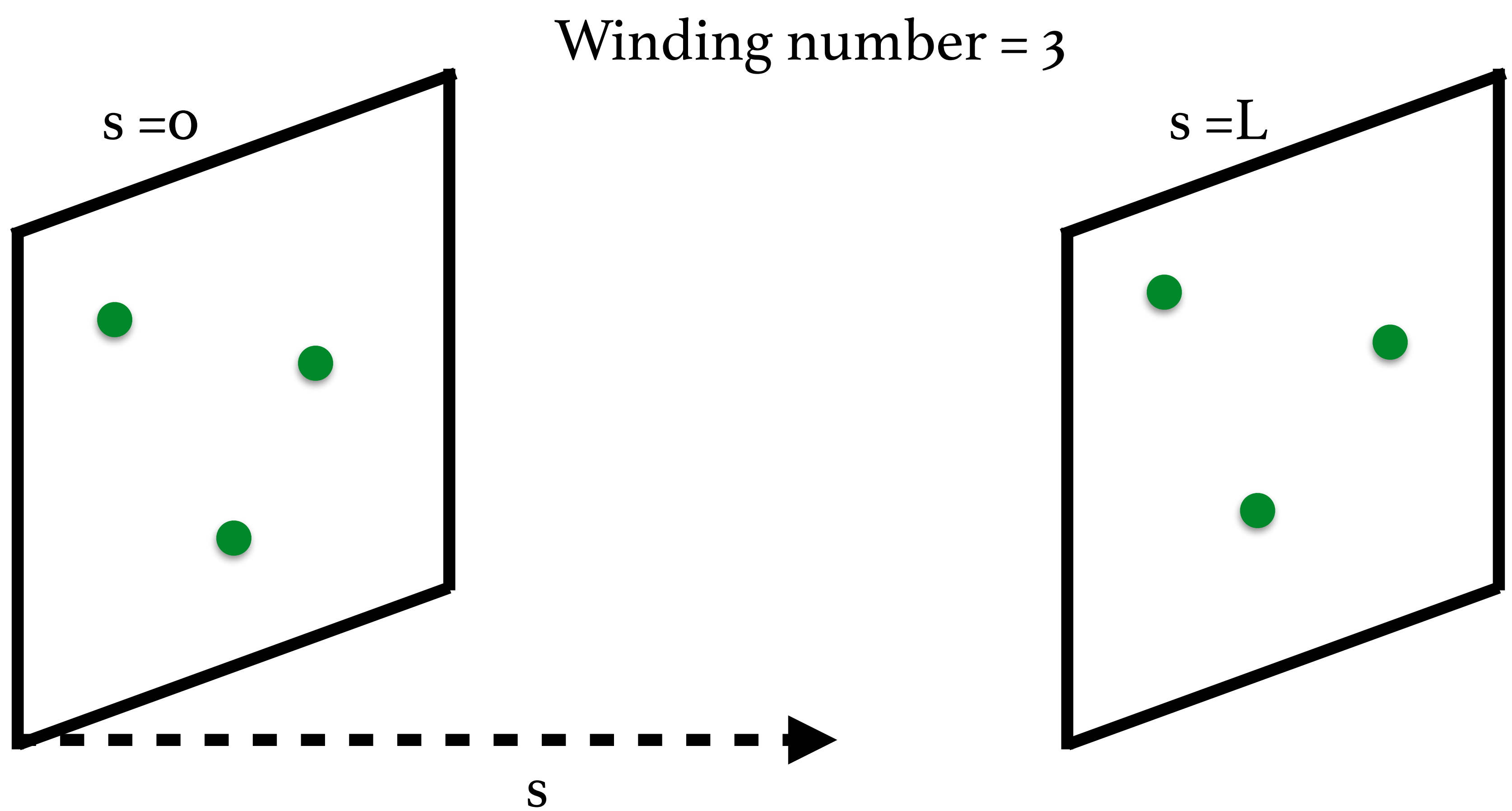
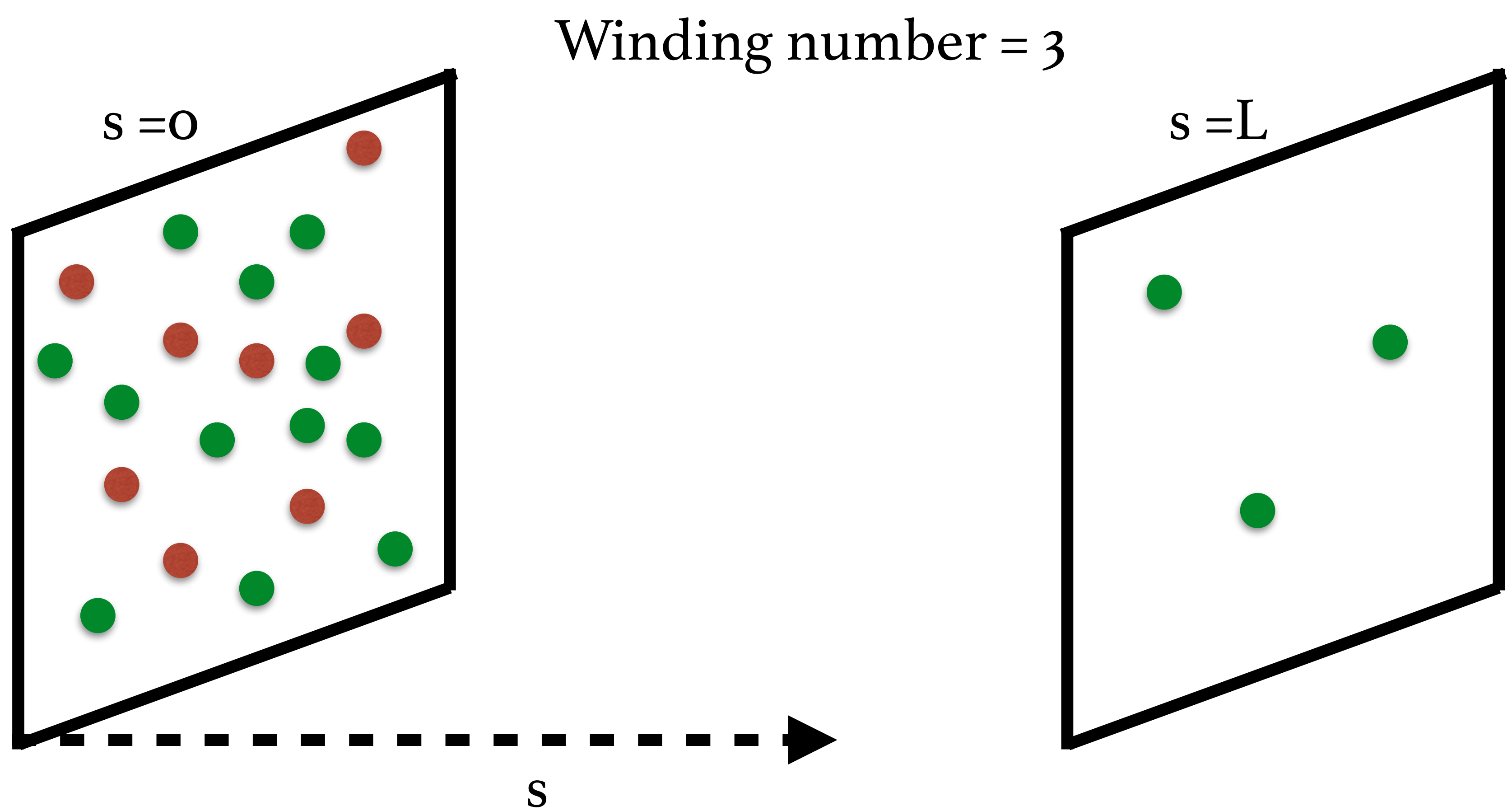


At weak coupling, instanton contribution is most important

- Instantons are the fixed point solutions of the flow equation
- Correlation between location of instantons on the two boundaries allows for exchange of energy/momentum
- Highly suppressed process, so difficult to observe

Topological Gauge Configurations - Strong Coupling



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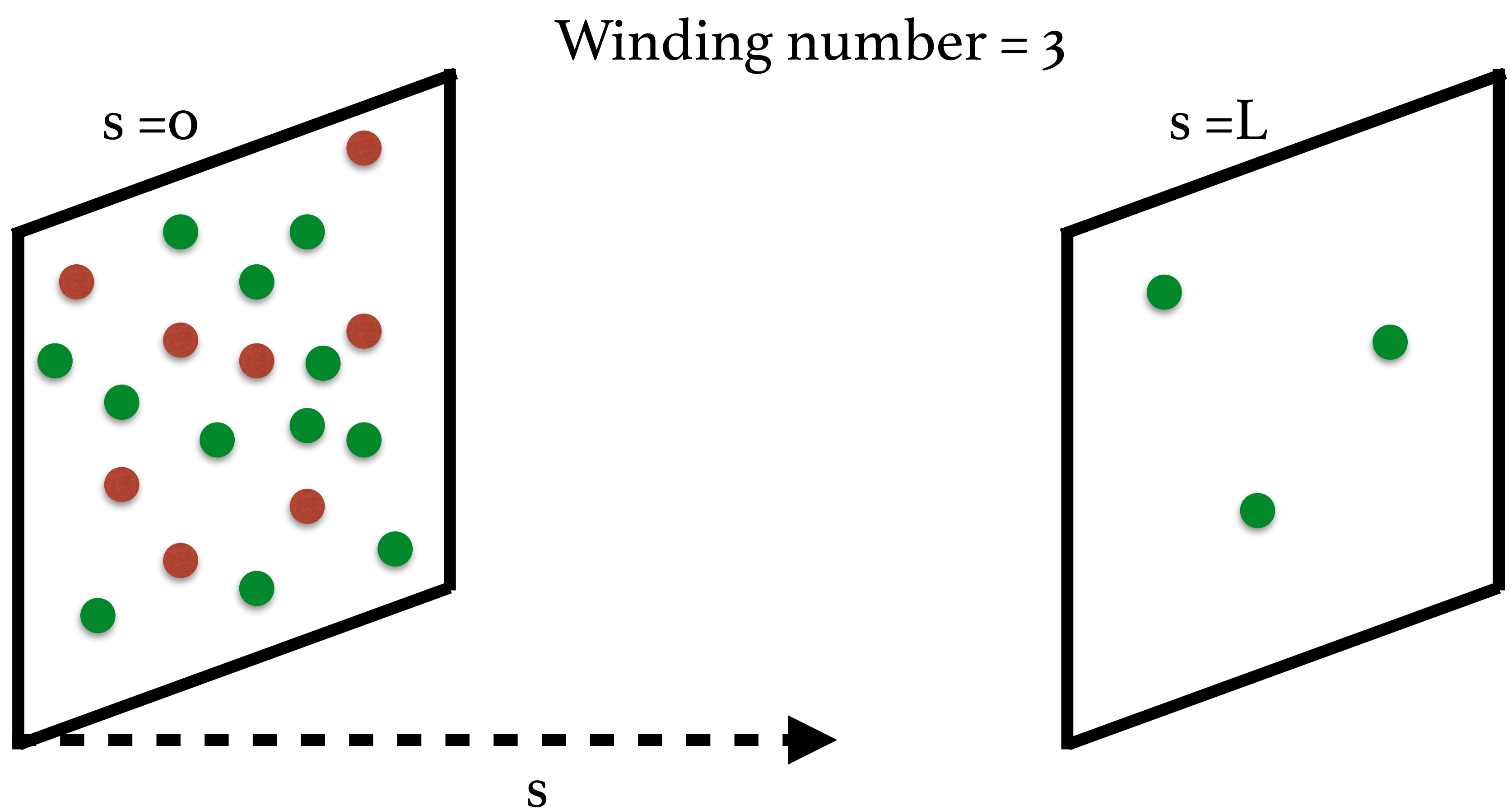

At strong coupling, need to include instanton-anti instanton pairs

- I-A pairs DO NOT satisfy equations of motion
- If flow for sufficiently long time, all pairs will annihilate
- If no correlation between location of instantons, boundaries do not exchange energy/momentum

Phenomenological Implications of Fluff

{Mirror Fermions with Soft Form Factors = Fluff}

Question 1: Is Fluff just a lattice artifact?

- Fluff is a lattice artifact if its effects are only seen in the UV
- Fluff decouples from all gauge fields with nonzero momenta
- Fluff does not decouple from classical (nonperturbative/topological) gauge fields, as they are fixed points of the flow equation

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Question 2: Phenomenological implications of Fluff?

- Standard Model and Fluff have weird nonlocal nonperturbative interactions
- Can the existence of Fluff be used to address any open questions in particle physics?

Phenomenological Implications

Strong CP Problem: $\bar{\theta}$ is unphysical if there exist massless colored particles

- Localize Higgs field on one boundary
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Cosmological Effects: Fluff could affect early Universe behavior

- Ricci flow smoothes out manifold in same as gradient flow
- Could Fluff decouple from gravity via Ricci flow?

Summary

- Proposal for fermion measure for chiral gauge theory

$$\Delta(A) = \prod_i \frac{\det\left[\not{D}(\bar{A}) - \Lambda_i \epsilon(s)\right]}{\det\left[\not{D}(\bar{A}) - \Lambda_i\right]} \qquad \partial_s \bar{A}_\mu = \frac{\xi \epsilon(s)}{|\Lambda|} D_\nu \bar{F}_{\nu\mu}$$

  - Combines domain wall fermions and gauge field smearing
  - Local theory if chiral fermion representation is anomaly free
  - Mirror fermions decouple due to exponentially soft form factors to gauge fields

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- Important open questions remain about this proposal
  - Proposal can be tested by simulating QCD with N_F Flavors
- Is there Fluff hiding in the Standard Model?